Development of the Energy-smart Production Management system (e-ProMan): A Big Data driven approach, analysis and optimization

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Development of the Energy-smart Production Management System (e-ProMan): a Big Data Driven Approach, Analysis and Optimisation

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Abstract:

Given the challenges in increasing energy prices and environmental issues, energy efficiency is becoming a major concern in manufacturing industries. To reduce energy consumption, manufacturing operations need to develop energy efficient techniques. This development will also help reduce GHG emissions and production costs. The aim of this research is to create a simulation methodology and investigate the modelling of thermal and energy management (called e-ProMan) across the manufacturing site.

By using simulations, the “e-ProMan” system generates a real-time, virtual, user-friendly factory model. A “Big Data” approach is taken in which a large set of data is acquired from both inside and outside the factory in order to analyse the correlation between work flow, data flow and energy flow to provide real-time decision making. In particular, five data sources are gathered including weather forecast, temperature and humidity sensors, machine energy consumption and production process and scheduling. The “e-ProMan” system is specifically designed to suit manufacturing operations of small and medium sizes to complement limited budget and lower resources especially in data gathering infrastructures.

Keywords: Energy Efficiency, Manufacturing SMEs, GHG emissions, Simulation methodology modelling.

1. Introduction

Recently, manufacturing industries have been confronted with increasing energy prices and environmental issues [4] [12]. Energy is now one of the major costs in manufacturing and is responsible for a significant proportion of CO_2 emissions in manufacturing. Electrical energy is the main energy used for equipment and machines [9][10]. The International Energy Agency (EIA) predicts that the world's energy consumption will rise by more than 7% per annum to 2035 [10]. The development of energy efficiency techniques in manufacturing systems is therefore crucial to reduce energy consumption, CO_2 emissions and also production costs.

There are many ways to reduce energy consumption and to make energy efficiencies such as using applications, switching off the lights, pulling out plugs, optimising machine tools and minimising energy consumption of machines and HVAC systems [15]. Increased energy efficiency can be achieved through energy management of heating, ventilating, and air conditioning (HVAC) [15]. In all manufacturing applications, facility HVAC systems account for around half of non-process energy consumption by end use [15]. With such a large amount of energy consumption attributed to HVAC, there is much room for improving efficiency and reducing energy consumption, particularly through the model-based smart energy management system supported with real-time ‘Big Data’, and the corresponding predictive control and optimization of the HVAC system [5]. Energy models working with large datasets can help in understanding the evolution of consumption patterns, predicting future energy trends, and providing the basis for optimizing the performance of large-scale manufacturing systems [1].

This paper presents a simulation-based approach to modelling thermal and energy management which considers the whole manufacturing system based on thermal and energy consumption and its implementation perspectives against the requirements of the energy-management system for production systems (e-ProMan) at manufacturing SMEs in particular. The approach is to use conventional equipment and tools that can be integrated in an industrial-feasible manner so as to give the flexibility and scalability for SMEs companies. The state-of-art for energy consumption reduction strategies, energy-saving methods and thermal management can be thus thoroughly pursued by developing and using performance measurement tools and optimal implementation.

2. Big Data within the Shopfloor Manufacturing Environment

The term ‘Big data’ refers to high-volume, high-velocity and/or high-variety information assets, which trend to double every 18 months and that need new processing system in order to provide enhanced decision making [3]. The data include government data holdings, company databases, sensor networks and public profiles on social networking sites that can be gathered from numerous sources [6].

In manufacturing, big data can aid productivity, product and process discovery and policy-making [6]. Extremely useful information can be provided by big data. This data can enable manufacturers to know their current situation and to learn more about their workforce - which is essential in increasing efficiency and also productivity [6]. For this research, the chosen big data are divided into 5 sections which are weather forecast, temperature sensors, machine energy consumption and production processes and production schedules.

2.1 Machine Energy Consumption

The Department of Energy (DOE) stated that machinery consumed 204 trillion Btu of energy [15]. In manufacturing processes, there are varieties of machines with each type of machine consuming different amounts of energy and not necessarily working simultaneously. Some of them are set as idle and some of them work half load; hence, this complexity can lead machine energy consumption to become big complex data [16].

2.2 Production Processes and Production Schedules

According to manufacturing complexity research, production planning and control is one of the main complexities in industrial manufacturing, which needs to be considered. This issue crucially deals with variety of products and uncertainty in customers' demand [8]. This information is one area of big manufacturing data that needs to be dealt with.

In this research, ARENA simulation programme is used to demonstrate production system including production processes and production schedules in order to illustrate energy flow and work flow, and calculate energy consumption and CO_2 emissions in each machine and process.

2.3 Temperature Variation and Control

Real-time temperature in a manufacturing plant also creates one of the big data sets that constantly changes due to the weather. Temperature sensors are used to acquire surrounding temperature in a manufacturing facility. In the different areas of the facility, the temperatures can be very different. In this research, 3D temperature sensor mapping data can be illustrated with the linkage between the temperature sensors and LabVIEW programme.

2.4 Forecastive Control Using Climate Data

To establishing an accurate forecastive control system, real-time weather forecast data needs to be acquired. The more climate data are frequently updated, the more precise forecastive data are provided [14]. There are a number of commercial weather forecast websites that offer real-time climate data such as Metoffice, BBC Weather, Metcheck, AccuWeather.com and Weather Channel. Numerical Weather Prediction model (NWP) is a weather prediction system that uses computer simulation. It is generally considered as the most reliable climate prediction system [14]. This research obtains predictive weather date from Met Office because the Met Office is the UK meteorological specialist, who uses NWP model for prediction.

3. Development of the e-ProMan System

The e-ProMan system demonstrates real-time, virtual friendly factory displays by using CAD models. This is a predictive system that proceeds by getting input from the big manufacturing data and the factory, and analysing the correlation of multi-dimensional star which are energy flow, data flow and work flow chart in order to make accurate real-time decision making possible (based on good investigation, modelling and simulation which has established the proper relationships) as shown in Fig.1.

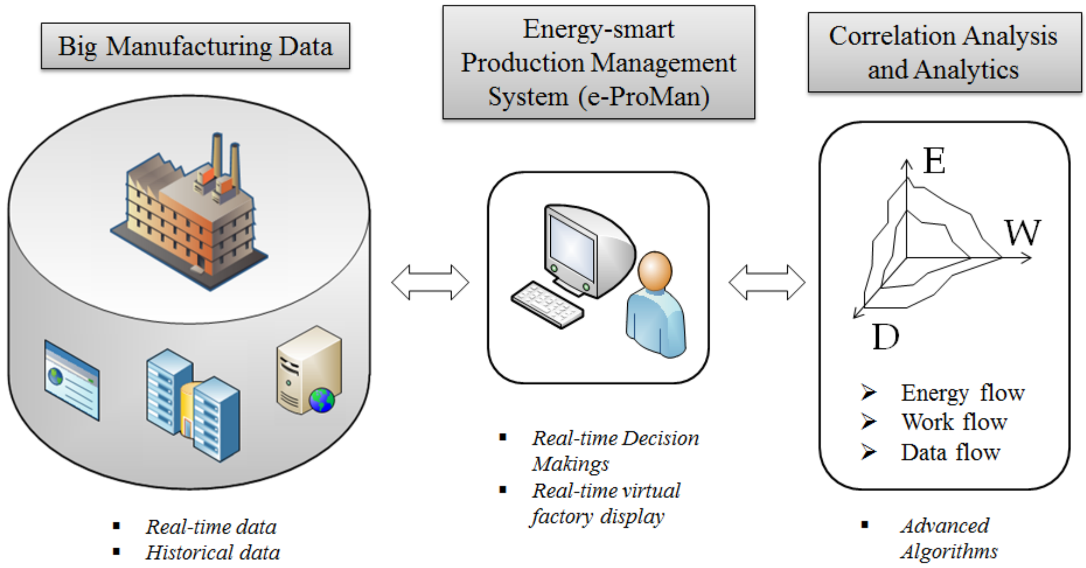


Fig.1. Architecture of the Energy-smart Production Management System (e-ProMan)

The big manufacturing data include weather forecast, temperature sensors, production processes, production schedules and energy consumption from machines such as CNC machines and HVAC system and includes both historical and real-time data. In order to gather the big manufacturing data, LabVIEW and Arena Simulation programmes are used as analysis and implementation tools. The e-ProMan system (1) monitors temperature in manufacturing facility with temperature sensors, (2) acquires production process and production schedule data via Arena Simulation programme and (3) measures energy consumption of machines by using power logger equipment.

This information is used to provide a thorough understanding of the relationship between the energy flow, data flow and work flow in the manufacturing environment. The development of a control system will proceeded from this understanding, followed by optimisation in order to minimise energy usage and GHG emissions.

4. Implementation Perspectives

LabVIEW programmes are widely used by scientists and engineers for virtual measurement and virtual friendly display [2]. In addition, Arena Simulation is considered one of the best simulation programmes that can model and simulate complex systems [13]. This research uses simulation methods to identify the feasibility of predictive control in manufacturing energy management system including energy flow, data flow and work flow.

4.1 Virtual Workshop and Forecastive Control

In this experiment, a LabVIEW programme is used to implement energy management system in typical manufacturing plant including data acquisition and virtual display. Arena simulation programme is used to simulate manufacturing processes and schedules. The e-ProMan system interfaces consist of 5 main panels which are machine energy measurement, Arena simulation in manufacturing production process, 3D temperature sensors mapping in manufacturing plant, weather forecast and HVAC system controller.

The e-ProMan system starts from acquiring 4 big data sources (machine energy consumption, production processes and production schedules, temperature in manufacturing plant and climate prediction - including historical and real-time data). This programme runs continuously and displays the results every second.

4.2.1 Heating, ventilation and air conditioning

The HAVC system controller part of the e-ProMan system needs to be set to provide a comfortable temperature in workplace. According to ideal HVAC temperature, the temperature needs to be set at a range between 16 and 19°C in order to provide the best working condition [5]. The logical simulation is based on mathematical formula and C language by using LabVIEW programme. The controller obtains weather prediction data from Met Office database and uses them to control the HVAC system. This system controls the workshop temperature by comparing the actual and historical temperature in the workshop and weather prediction data in the next hour period from the forecast website. If the temperature in the workshop is higher than 19°C or lower than 16°C, the heating and air conditioning system will be operated. When the temperature is in the range between 16 and 19°C, the HVAC system will be turned off in order to reduce the consumption of energy.

The simulation system runs to provide a comfortable temperature in the manufacturing plant and also define over energy usage results continuously. This HVAC controller cannot only be used for controlling environmental temperature, but it can also be used as forecastive controller in nearly future considering weather forecast and current temperature, which could minimise the energy usage.

4.2.2 Energy Consumption

According to the differential temperature of inside and outside, HVAC system requires energy to heat and cool the environment temperature in the shop floor. The energy usage calculation of HVAC system can be represented as,

$$Q = \rho 0CpV(\Delta T) \text{ or } Q = \rho 0CpV|Ti-To| \quad (1)$$

Where Q is energy used to maintain the building temperature, ρ0 is the density of outside air, Cp is the specific heat of air, V is the volumetric flow rate of air (volume of air change in one hour), Ti is the temperature outside the building and To is the temperature inside the building [7]. The general of specific heat of air is 1 kJ/Kg · °C at normal atmospheric pressure and standard value of air density is 1.2754 kg · m-3 [7].

4.2.3 Carbon Emission

The carbon footprint of a manufacturing system can be evaluated by using the equation of Carbon Emission Signature (CESTM) [11]. Thus, the carbon emitted can be calculated by multiplying energy consumed (EC) to Carbon Emission Signature (CES) as shown in the equation below.

$$CE = EC\ (GJ) \text{ x } CES\ (kgCO_2/GJ) \quad (2)$$

Moreover, there can be more than one primary energy sources than an electrical grid which might include coal, natural gas, petroleum, biofuel, hydro, solar, wind, geothermal, earth, wave and tidal. Each of these can be represented as function: C (coal), NG (natural gas), P (petroleum), B (biofuel), H (hydro), S (solar), W (wind), G (geothermal), E (earth), W (wave) and T (tidal). The Carbon Emission Signature (CES) can be calculated by the summary of fractions of the primary sources multiplied by the conversion efficiency (η) for each primary energy source as defined below [7].

$$CES = \eta \text{ x } [112x\%C + 49x\%NG + 66x\%P] \quad (2)$$

The coefficients of coal (C), natural gas (NG), and petroleum (P) are 112, 66, and 49 respectively; they are the kilograms of carbon emitted per gigajoule of heat released and are an inevitable fate of combustion in each case. The conversion efficiency (η) = 0.34 is common and is applied in this research [7].

4.2 Correlation Analysis and Analytics

4.2.1 Temperature vs Quality

In manufacturing environment, controlling the temperature is necessary for workers and machines. Due to too high or/and too low temperature, people and equipment could get into bad working conditions and this would lead to lower quality of work. Hence, the workshop temperature needs to be controlled between 16 and 19°C in order to make comfortable working environment.

4.2.2 Energy Flow vs Work Flow

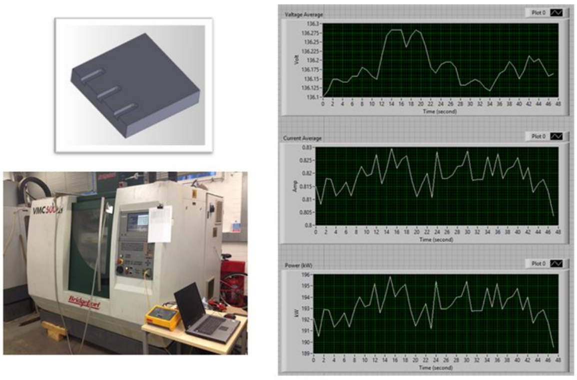
Energy is mostly consumed from production processes in manufacturing. The more manufacturing process runs, the more energy is consumed; thus energy flow is positively correlated with work flow. Unbalanced work load would lead to extra energy usage. For instance, if the production operates overloads of work, machines and equipment will need more energy to manufacture products. If low work load provides for the operation, the manufacturing may face a standing-by situation which causes energy wastage. Hence, managing work flow for manufacturing processes is a crucial aspect that can help minimize energy costs.

4.2.3 Optimization

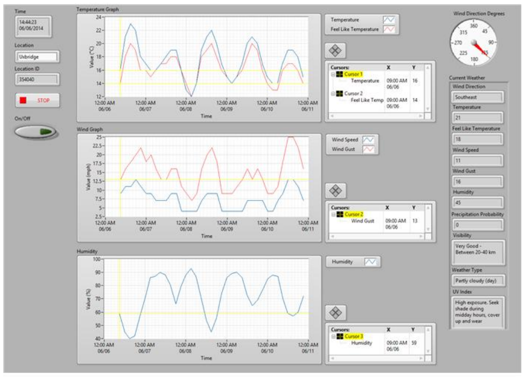
With regards to energy flow, data flow and work flow, this predictive system proceeds by analysing their multi-dimensional star correlation in order to minimise energy consumption and balancing the work flow. This system could make accurate real-time decisions based on the good investigation, modelling and simulation which have established the proper relationships.

4.3 System Design and User Interface

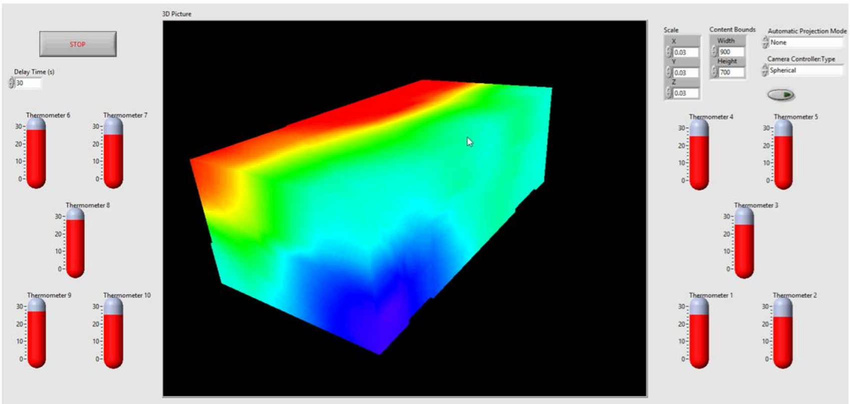
e-ProMan system's user interface consists of 4 main elements which are machine energy measurement, temperature and forecast control on HVAC, 3D Temperature Sensor Mapping in Manufacturing Plant and HVAC System Controller as shown in Fig.2. First, the power logger experiment is used to measure the energy consumption from a CNC machine when it is milling in specific material, job time and tools. It gives results of voltage, current and power and links to LabVIEW programme. The Weather forecast user interface is used to acquire the current weather and weather forecast from the chosen weather website which shows temperature, humidity, wind speed, wind direction and etc. for the next 5 day's period. 3D sensor mapping illustrates the temperature flows in each area in the lab. The red colour indicating hot areas and the blue colour indicating cold areas. As shown in Fig 2, the higher area has higher temperature than the lower ground since hot air travels upwards from the ground. Lastly, the controller consists of HVAC temperature and fan speed. The HVAC system uses a simple logic to choose between heating and cooling by comparing inside and outside temperature. According to the climate predictions, this system can be turned on and off automatically in order to minimize energy consumption.



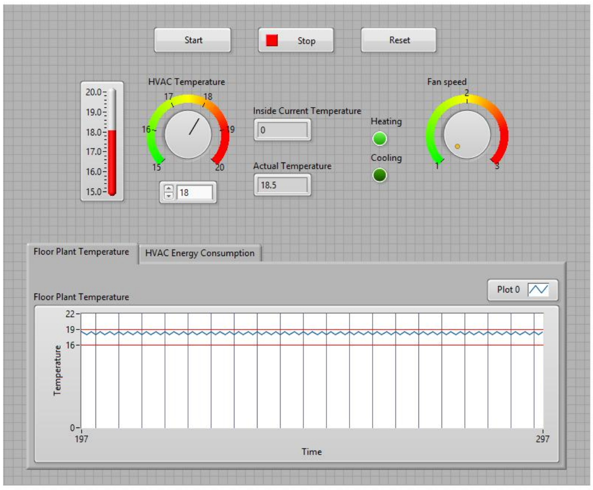
(a)



(b)



(c)



(d)

Fig.2. e-ProMan system: (a) Machine Energy Measurement; (b) Temperature and Forecast Control on HVAC;
(c) 3D Temperature Sensor Mapping in Manufacturing Plant; (d) HVAC System Controller

5. Application Perspectives and Preliminary Results

In this simulation, the thermal generation and consumption are considered. The simple example experiment shown was run at 1pm in London. The results of e-ProMan system consisted of two parts, which were actual temperature at shop floor and energy consumption of HVAC shown in Fig.3 and 4, respectively. Fig. 3 shows the floor plant temperature over the period of time. The workshop temperature starts at approximately 12°C and increases to 17°C by heating system. After, the trends were similar, where peaks and valleys were consistent between 16 and 19°C across different time scales by controlling the HVAC system. Total energy consumption was 130.7kW during the time period as shown in Fig. 4. Clearly, more energy was consumed at the beginning because the HVAC system needed a large amount of energy to increase the overall ambient temperature in the shop floor. The system consumed around 5.7kW per second until the temperature rose to 17°C. Then, the energy consumption dropped below 0.7kW per second in order to keep surrounded temperature between 16 and 19°C by continuously turning on and off HVAC system.

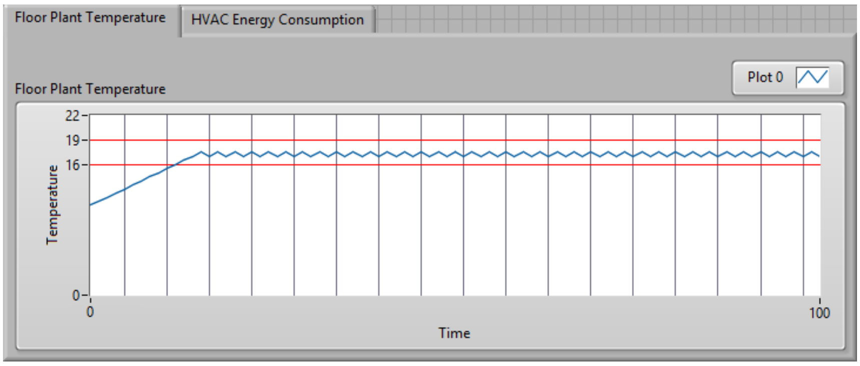


Fig.3. The Result of Floor Plant Temperature

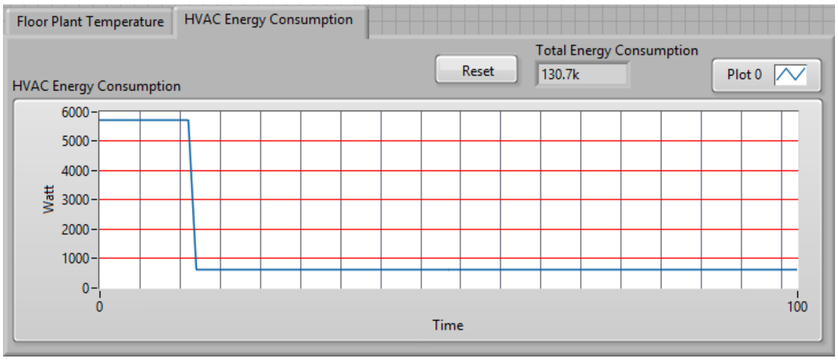


Fig.4. The Result of HVAC Energy Consumption

6. Conclusions

In this paper, a simulation-based approach is presented to developing thermal and energy management systems applied to SME manufacturing environments, supported with real-time ‘Big Data’, and the corresponding predictive control and optimization analytics. A prototype system - e-ProMan is developed, which can enhance efficiency and reliability of energy management by intelligently managing a variety of machines, processes and schedules. Moreover, the approach and associated system (e-ProMan) can be used to control, optimize and manage the use of energy on manufacturing shop floors by real-time measurement and analysis, so to understand overall manufacturing system flows including energy flow, data flow and work flow. This research will further be focused on work flow in the manufacturing system and exploring the quantitative relationships among the three flows to develop more complex and real manufacturing site based models for validation purposes.

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